Design Optimization of Combined Expansion Tube-Axial Splitting as Impact Energy Absorber

Yuwono Budi Pratiknyo[1,2], I Wayan Suweca[1], Rachman Setiawan[1]

[1)]Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung,
Jln Ganesa No 10, Bandung, Indonesia
[2)]Faculty of Engineering, Universitas Surabaya,
Jln Kalirungkut, Surabaya, Indonesia

*Corresponding e-mail: rachmans@edc.ms.itb.ac.id

ABSTRACT – In This paper, a single objective optimization based on response surface methode is adopted in order to calculate the optimalexpansion tube-axial splitting model parameter. Expansion tube-axial splitting as impact energy absorber applied to overcome collision accidents on passenger trains. Impact energy absorber will absorb the energy that occurs during an accident, so passengers are safe. The dimensions of the expansion tube axial splitting module are influenced by several parameters including tube tickness (t), Inner diameter of tube (D_1) and outer diameter of Dies (D_2). That are influential with the total energy absorbed by the impact absorbing module. Formulations that have been obtained in previous studies are optimized to get the best dimensions.

This study resulted in the selection and optimization method of the design of the impact absorbent module that fits the parameters of the impact absorbent module from various module geometry alternatives taking into account the availability of space.

Keywords: Design optimization, crashworthiness, expansion tube, axial splitting, impact energy absorber

1. INTRODUCTION

The combined expansion tube-axial splitting of deformable rigid tube developed as new mechanism as impact energy absorber. The impact absorbing structure consists of two circular tube forming dies, each dies allowing the tube to expand and to split. The latter is used to meant move away radially the debris after expansion and splitting, so that the absorption process can continue without being obstructed by the debris itself [1]. This combination expansion tube-axial splitting module produces absorption impact characteristics wherein the absorption of the second force of the impact absorbing module is more stable. Enhancement on pipe thickness will cause force enhancement that is able to be absorbed by module [2].

The minimization of the impact of accidents is one of the ways to reduction the effect of accident due to collisions on mass transportation (railways). The impact energy absorber (IEA) module is one of the most important components in the application of crashworthiness technology to improve the safety of transportation facilities. The effective mechanism for absorbing impact energy is through the modular deformation of the module structure. The effect of impact energy absorber, the impact energy and impact force which passed to the main structure of the vehicle will be limited during a collision, so the impact of collision on passengers or cargo can be minimized [3]. In its application, the IEA requires a very important component, which is an impact energy absorbing module. The impact energy absorbing module is one of the most important components in applying crashworthiness technology to improve the safety of transportation facilities. The ideal impact absorbing module is an impact absorbent module that is able to regulate the maximum impact strength permitted throughout a stroke in addition to the effect of elastic loading [4]. In previous studies Ezra and Fay have classified specific energy (Se) and stroke efficiencies (Stc) in several impact absorbent modules [5]. Alghamdi has reviewed several forms of impact energy absorbing. modules and produced several forms of deformation [6]. IEA in plastic deformation can be categorized by structure and material. Based on the structure can be divided into drum [7], circular tube [8] [9], tubular ring [10], square tubes [11] [12] [13] [14] [15] [16], corrugated tubes [17], multi corner columns [18], frusta [19], struts [20], honeycomb cells [21], sand-wich plates [22], circular thin-walled tubes [23], top-hat thin-walled sections [24].

The combined expansion tube-axial splitting of deformable rigid tube developed as new mechanism as shown in Figure-1

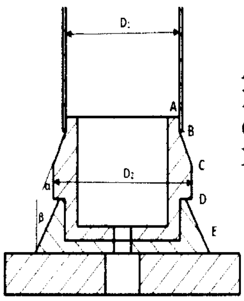

Figure-1. Segmented process combined expansion tube-axial splitting

The calculation of combined expansion tube-axial splitting can be explained as follows.

1. Pre-compacting (Zone A-B), at this stage the tube is given a load so that the tube enters the dies and the material is still in the elastic zone.

2. Expansion Process (Zona B-C), at this stage that a new formula has been found to calculate the mean load. The formula mean load (Pm) is as follow:

$$Pm = (\pi t)(D_1 + t)(\sigma_o)\frac{-\frac{K}{t}+ln|D_2-D_1|}{\frac{1}{D_1}+\frac{K}{t}} \quad (1)$$

$$K = \left(\frac{\mu+\tan}{2\tan\alpha(1-\mu\tan\alpha)}\right) \quad (2)$$

3. Extendex Expansion Process (Zona C-D), at this stage, Tube has the same emphasis as the previous process, so that at this stage it has the same formula as the previous stage
4. Axial Splitting Process (Zona D-E), at this stage that a new formula has been found to calculate the prediction of maximum expanded diameter, that tube will be collapse.

$$\frac{Ln\ \ X}{(D_x)} - \frac{K/_t+Ln\ \ _1}{D_x} \leq \frac{\varepsilon\pi D_x tE(t+K)}{(\pi t)(D_1+t)(\sigma_o)D_1 t} \quad (3)$$

$$K = \left(\frac{\mu+\tan}{2\,\mathrm{ta}\quad(1-\mu\,\mathrm{ta}\quad)}\right) \quad (4)$$

The purpose of this paper is to arrange the methodology for selecting and optimizing the design of impact absorbers modules that meet the parameters of impact absorbers from various alternative geometry modules taking into account the availability of space

2. METHODOLOGY

Design Of Experiments (DOE)

Design of experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. An understanding of DOE first requires knowledge of some statistical tools and experimentation concepts. Although a DOE can be analyzed in many software programs, it is important for practitioners to understand basic DOE concepts for proper application.

The most commonly used terms in the DOE methodology include: controllable and uncontrollable input factors, responses, hypothesis testing, blocking, replication and interaction.

- *Controllable input factors*, or *x* factors, are those input parameters that can be modified in an experiment or process. For example, in cooking rice, these factors include the quantity and quality of the rice and the quantity of water used for boiling.
- *Uncontrollable input factors* are those parameters that cannot be changed. In the rice-cooking example, this may be the temperature in the kitchen. These factors need to be recognized to understand how they may affect the response.
- *Responses*, or output measures, are the elements of the process outcome that gage the desired effect. In the cooking example, the taste and texture of the rice are the responses

Response Surface Methodology (RSM)

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of *experiments*, the objective is to optimize a *response* (output variable) which is influenced by several *independent variables* (input variables). An experiment is a series of tests, called *runs*, in which changes are made in the input variables in order to identify the reasons for changes in the output response. RSM was developed to model experimental responses (Box and Draper, 1987), and then migrated into the modelling of numerical experiments. The difference is in the type of error generated by the response. In physical experiments, inaccuracy can be due, for example, to measurement errors while, in computer experiments, numerical noise is a result of incomplete convergence of iterative processes, round-off errors or the discrete representation of continuous physical phenomena (Giunta et al., 1996; van Campen et al., 1990, Toropov et al., 1996).

The application of RSM to design optimization is aimed at reducing the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise. The problem can be approximated with smooth functions that improve the convergence of the optimization process because they reduce the effects of noise and they allow for the use of derivative-based algorithms. Venter et al. (1996) have discussed the advantages of using RSM for design optimization applications.

3. RESULTS AND DISCUSSION

Optimization Process

The problem optimization can be explain as follow:

<u>Design Variable</u> :

- tube tickness (t),
- inner diameter of tube (D_1). and
- outer diameter of Dies (D_2)

<u>Objective function</u> :

Maximize the specific energy (Se)

Se = EA/m (5)

Maximize stroke effeciency (Le)

Le = L/Lo (6)

Maximize crushing force effeciency (CFE)

CFE = Pm/Ppeak (7)

<u>Equality constrain function:</u>

- $0 \leq L/Lo \leq 1$ (8)
- $0 \leq P_m/P_{peak} \leq 1$ (9)
- $0 \leq m \leq m_{ijin}$ (10)
- $0 \leq L_o \leq L_{ijin}$ (11)
- $D_2 \leq D_x$ (12)

$$\frac{LnD_X}{(D_x)} - \frac{K/_t+Ln\ \ _1}{D_x} \leq \frac{\varepsilon\pi D_x tE(t+K)}{(\pi t)(D_1+t)(\sigma_o)D_1 t} \quad (13)$$

Where :

EA	= total energy absorbed (J)
m	= module mass (kg)
L	= length after collision (mm)
Lo	= length before collision (mm)
Pm	= mean crushing force (N)
Ppeak	= Peak crushing force (N)

The steps using response surface can be explain as follow:

1. Determine factors, number and range of levels for each factor.
2. Determine the response and learn how to measure it.
3. Compile a first order experimental design.
4. Conduct an experiment according to the design of the first order.
5. Processing the results of the first order experiment. Draft a second order experiment.
6. Conduct experiments according to the design of order II.
7. Processing the results of the second order experiment
8. Determine the optimization model.
9. Determine optimum conditions

First Orde Calculation

Table-1 shows the first order calculation at iteration # 1

Table-1. The first order calculation at iteration # 1

No	t	D1	D2	Pm
1	0,1	10	11	-1099,66
2	0,1	10	81	-251,2976
3	0,1	80	11	#NUM!
4	0,1	80	81	-8858,93
5	2	10	11	-19533,23
6	2	10	81	281856,26
7	2	80	11	#NUM!
8	2	80	81	-173922,35

Range t → $0{,}1 \leq t \leq 2$
Range D₁ → $10 \leq D_1 \leq 80$
Range D₂ → $11 \leq D_2 \leq 81$
Range Level Not Fulfilled

Table-2 shows the first order calculation at iteration # 2

Table-2. The first order calculation at iteration # 2

No	t	D1	D2	Pm
1	0,5	20	25	4961,31
2	0,5	20	90	30920,76
3	0,5	80	25	Not devined
4	0,5	80	90	47808,41
5	2	20	25	199294,69
6	2	20	90	593805,28
7	2	80	25	Not devined
8	2	80	90	1275658,11

Range t → $0{,}5 \leq t \leq 2$
Range D₁ → $20 \leq D_1 \leq 80$
Range D₂ → $25 \leq D_2 \leq 90$
Range Level Not Fulfilled

Table-3 shows the first order calculation at iteration # 3

Table-3. The first order calculation at iteration # 3

No	t	D_1	D_2	Pm
1	0,5	20	81	29567,03
2	0,5	20	90	30920,76
3	0,5	80	81	-44117,51
4	0,5	80	90	47808,40
5	2	20	81	573232,37
6	2	20	90	593805,28
7	2	80	81	-173922,34
8	2	80	90	1275658,10

Range t → $0{,}5 \leq t \leq 2$
Range D₁ → $20 \leq D_1 \leq 80$
Range D₂ → $81 \leq D_2 \leq 90$
Range Level Not Fulfilled

Table-4 shows the first order calculation at iteration # 4

Table-4. The first order calculation at iteration # 4

No	t	D_1	D_2	Pm
1	0,5	20	83,02	29887,40
2	0,5	20	90	30920,76
3	0,5	80	83,02	0,00
4	0,5	80	90	47808,40
5	2	20	83,02	578101,12
6	2	20	90	593805,29
7	2	80	83,02	521767,09
8	2	80	90	1275658,11

Range t → $0{,}5 \leq t \leq 2$
Range D₁ → $20 \leq D_1 \leq 80$
Range D₂ → $83{,}2 \leq D_2 \leq 90$
Range Level Fulfilled

Second Orde Calculation

The seconde orde calculation used 3^k factorial (*Three Level Factorial Design*)

Table-5 shows the second order calculation

Table-5. The second order calculation

No	t	D_1	D_2	Pm
1	0,5	20	83	29884,37
2	0,5	20	86,5	30416,21
3	0,5	20	90	30920,76
4	0,5	50	83	59493,91
5	0,5	50	86,5	62001,71
6	0,5	50	90	64279,71
7	0,5	80	83	-257,70
8	0,5	80	86,5	30610,29
9	0,5	80	90	47808,40
10	1,25	20	83	221483,77

11	1,25	20	86,5	224719,29
12	1,25	20	90	227788,81
13	1,25	50	83	469465,91
14	1,25	50	86,5	484959,34
15	1,25	50	90	499032,98
16	1,25	80	83	162627,90
17	1,25	80	86,5	354137,27
18	1,25	80	90	460836,75
19	2	20	83	578055,03
20	2	20	86,5	586137,49
21	2	20	90	593805,29
22	2	50	83	1253050,98
23	2	50	86,5	1292275,82
24	2	50	90	1327906,19
25	2	80	83	517703,30
26	2	80	86,5	1004460,96
27	2	80	90	1275658,11

Validation

Theoritical Calculation

Table-6 shows the theoritical calculation with t = 1 and 1,5, D_1 = 54 mm and D_2 = 60,48 mm

Table-6. Theoritical calculation with t = 1 and 1,5, D_1 = 54 mm and D_2 = 60,48 mm

No	t	D_1	D_2	Pm
1	1	54	60,48	281037,67
2	1,5	54	60,48	357883,20

Experimental Result.

Table-7 shows the experimental result, with t = 1 and 1,5, D_1 = 54 mm and D_2 = 60,48 mm

Table-6. Theoritical calculation with t = 1 and 1,5, D_1 = 54 mm and D_2 = 60,48 mm

	T	D_1 (mm)	D_2 (mm)	Pm (N)
1	1	54	60,48	218600
2	1	54	60,48	262610
3	1	54	60,48	254450
4	1	54	60,48	262240
5	1	54	60,48	228800
6	1	54	60,48	225300
7	1	54	60,48	222800
8	1	54	60,48	230900
9	1	54	60,48	338170
10	1,5	54	60,48	349340
11	1,5	54	60,48	357000
12	1,5	54	60,48	372160

Numerical Result

Software: LSDYNA Prepost V4.5 dengan solver R9.10
Model : Lagrangian
Element : Quadrangular element with t = 1.5 mm, D_1 = 54 mm and D_2 = 60,48 mm
Loading : Impactor 107 kg, impact speed 6 m/s
Material : API 5L Grade B for tube, rigid material for dies mild steel properties.
The numerical calculation of combined expansion tube-axial splitting as shown in Figure-2 and Figure -3

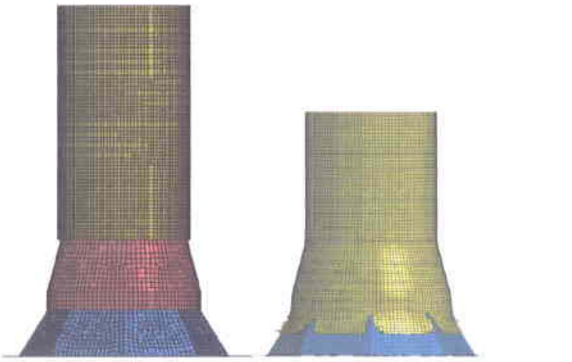

Figure-2. Segmented process combined expansion tube-axial splitting

Figure-3. Comparison numerical and experimental result of combined expansion tube-axial splitting

4. CONCLUSIONS

The application of RSM to design optimization have been reducing the cost of expensive analysis methods (e.g. finite element method or experimental) and their associated numerical noise. The problem can be approximated with smooth functions that improve the convergence of the optimization process.

Multi objective optimization has been applied to combined expansion tube-axial splitting, where optimal decisions need to be taken in the presence of trade-offs between two or more objectives

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